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'Acid Rain'

The Potential for Saskatchewan

by
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Department of Biology
University of Saskatchewan
Saskatoon, Saskatchewan

1980

Prepared for
The Saskatchewan Environmental Advisory Council

The Saskatchewan Environmental Advisory Council is a public advisory body to the Minister for the Saskatchewan Department of Environment. The Council is composed of representatives from agriculture, industry, labour, university, and other interest groups. The Council reviews government policies and programs relating to environment, attempts to identify potential environmental problems, and examines government public involvement programs relating to environmental issues.

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Preface

The Saskatchewan Environmental Advisory Council commissioned a study on the subject of acid rain for two principal reasons. First, given the present direction of federal and provincial energy planning — more specifically, the priority assigned to development of heavy oil and tar sands deposits — it can safely be predicted that acid rain will become an increasingly prominent issue for Saskatchewan. Second, it was Council's consensus that despite the growing number of reports and studies on acid rain, few of these focused specifically or sufficiently on Saskatchewan. Council felt that more attention should be given to the susceptibility of Saskatchewan environments to acidification, and this was designated the primary objective for this report.

The report was prepared for Council by Dr. U. T. Hammer, a biologist at the University of Saskatchewan and a member of Council. The text and conclusions of the report are the work of Dr. Hammer. The recommendations were formulated by Council on the basis of the report.

The report raises as many questions as it answers, and further studies are clearly in order. It is Council's consensus that the time to initiate this research and appropriate mitigative measures is now. The acid rain problem is not yet critical in Saskatchewan, but could easily become so. A passive approach to the problem has not been effective in other jurisdictions, and there are no grounds upon which to conclude that it would work in Saskatchewan. This is perhaps the report's most significant finding: that acid rain need not become a major issue for Saskatchewan if sufficient foresight, initiative, and regulatory stringency can be mobilized.

Dr. N. O. Nielsen,
Chairman
Saskatchewan Environmental Advisory
Council

Foreword

The most important environmental problem in Canada today is that of acid precipitation. Acid rain is rapidly leading to the deterioration of thousands of lakes in eastern Canada, and particularly in Ontario. In addition to the elimination of fish, acid precipitation leads to lower fertility of soils, and crop and forest production are reduced. Plants may be eliminated and deterioration of buildings and machinery can result.

In this paper acid precipitation is defined and its history in Europe and eastern North America outlined. The environmental effects of acid rain are delineated. The scene is then shifted to western Canada where the sources of sulphur and nitrogen oxides are determined and future projections made. Research on emission effects in Alberta is discussed.

The concluding section of the paper deals with Saskatchewan. Its aquatic and terrestrial ecosystems are examined with regard to their sensitivity to acid rain. Using predictions of sulphur outfall as well as some available meteorological data, conclusions are drawn as to the susceptibility of Saskatchewan environments to acid precipitation.

Table of Contents

	Page
Introduction	1
The Nature and Origin of Acid Rain	2
The History of Acid Rain	4
Long Range Transport of Atmospheric Pollutants	7
Environmental Effects of Acid Precipitation	8
Aquatic Ecosystems	8
The Chemico-physical Environment	8
Fish	9
Aquatic Plants	9
Aquatic Invertebrates	10
Terrestrial Ecosystems	10
Soils	10
Vegetation	11
Human Health	12
Corrosion	12
Acid Producing Emissions and their Effects on the Prairie Provinces	13
Sources of Emissions	13
Deposition of Emissions	17
Environmental Effects	20
Soils	20
Vegetation	20
Human and Other Animal Populations	21
Corrosion	22
Water	22
Susceptibility of Saskatchewan Environments to Acidification	23
Geology, Soils and Water Quality	23
Susceptibility of Lakes to Acidification	25
Precipitation Data and Their Implications	28
Conclusions	30
Recommendations	31
References Cited	32

List of Figures

Page

Figure 1. Schematic representation of the main components of the atmospheric sulphur budget from synthetic crude oil plants in a northern environment..... 3

Figure 2. The trends in pH of acid precipitation in eastern North America at about ten year intervals..... 5

Figure 3. The distribution of sulphur emissions (tonnes/day), present (1978) and projected (2006), according to industry source..... 14

Figure 4. Synthetic crude oil production in Alberta including projections to 2006..... 15

Figure 5. Annual and cumulative sulphur emissions from energy industries in Alberta, 1920 to 2006..... 16

Figure 6. Variations in sulphate sulphur content of various precipitation episodes in central Alberta, 1969..... 19

Figure 7. Geological and vegetational zonation of Saskatchewan..... 24

Figure 8. The projected distribution of SO_4 — S (kg/ha/yr) in the year 2006 using the maximum rate of development of synthetic crude oil production and assuming Flin Flon emissions remain the same..... 27

List of Tables

Table 1. Canadian emissions (tons) of some air contaminants for 1974..... 6

Table 2. Local effects of SO_2 on socio-economic functions of vegetation..... 12

Table 3. Annual emissions (tons) of some air contaminants in Alberta, Manitoba and Saskatchewan, 1974..... 13

Table 4. Observed sulphur emissions from industries in Alberta in 1978..... 15

Table 5. Chemical data for waters of some northern Saskatchewan lakes..... 23

Table 6. Emissions of NOx and SO_2 from Saskatchewan sources (tons / year)..... 29

Table 7. CANSAP data summary for precipitation at Cree Lake, Kindersley, and Wynyard stations, 1978..... 29

Introduction

The problem of acid rain has been much publicized by the Saskatchewan news media during the last year. The specific cases cited were usually in Europe or the eastern United States or Ontario. The most frequent reference was to the "death of lakes" based on the drastic effect of acidic waters on their fish inhabitants. Some of the articles and editorials, however, were specifically concerned about the potential for acid rain emanating from the development of the synthetic crude oil reserves of the Alberta oil sands*. With the increased development of the oil sands near Fort McMurray and in the Lloydminster-Cold Lake region over the next decade, the potential for acid precipitation would be augmented by increased emissions.

In 1976, Odén said that "the increasing acidity of the atmosphere is . . . the most interdisciplinary environmental problem we have at present. Soils and surface waters are affected; plant growth is retarded; ecosystems are changed; the biota in the lakes and rivers are changed; some organisms die; microorganisms, pathogens and soil fauna change their activity and living patterns; deterioration of buildings takes place as well as corrosion in a wide sense; and human health is affected" (50).

The problem of acid rain is not a new one. Scientists in Europe and particularly in Scandinavia have been monitoring and studying the problem since the 1950's (20). North American scientists have more recently become cognizant of the problem in eastern North America and have studied it intensively during the 1970's. It is well documented, particularly in Europe, that the acidity of rainfall has increased over the last two decades.

The most noticeable effect, other than the drastic denudation of vegetation in the vicinity of large emitters such as at Sudbury and Trail, has been the decreasing pH of lakes located on granitic rocks and the loss of their fish populations. This has been particularly evident in Scandinavia (southern Norway, western Sweden), Ontario and north-eastern United States. This information aroused great public concern in those particular areas but also in regions where the potential for damage from large emitters exists.

*Saskatoon Star Phoenix 1979, Nov. 3, p. D1; Nov. 7, p. C18; Regina Leader Post, 1979, Nov. 24, p. 6; Dec. 1, p. 30; Dec. 21, p. 45; 1980, Mar. 7, p. 26.

The Nature and Origin of Acid Rain

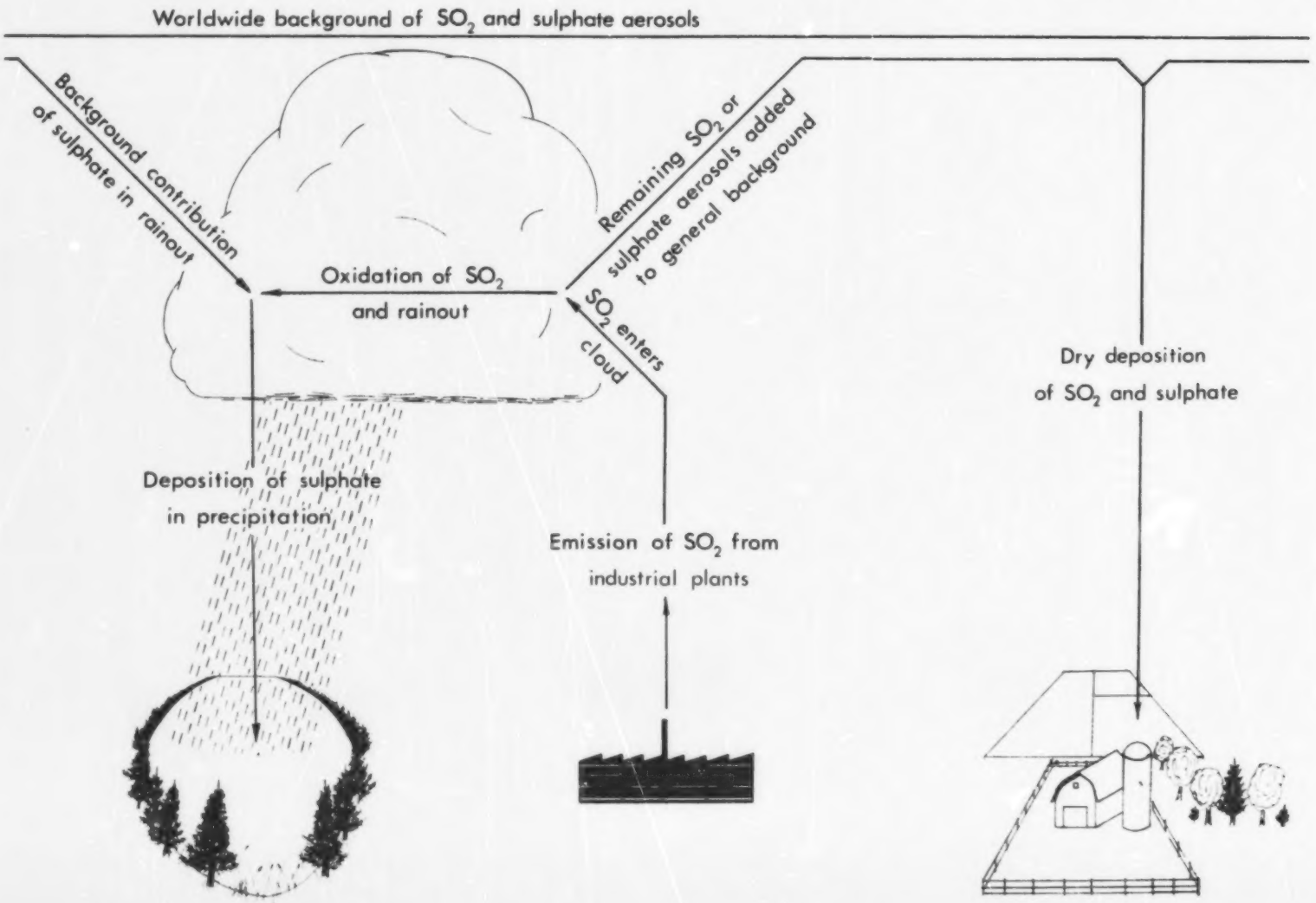
The presence of hydrogen ions (H^+) in an aqueous solution is synonymous with acidity. Acidity is commonly measured as pH, the negative logarithm of the hydrogen ion concentration on a scale of 0 to 14 with 7 a neutral solution. More hydrogen ions reduce the pH. Since the scale is logarithmic, solutions of pH 6, 5 and 4 contain one, 10 and 100 microequivalents per litre (μeq/L) of acidity (H^+).

How does rain become acid? Water in the atmosphere is derived from evaporation of water from the earth's surface and from transpiration by plants. This water vapor condenses on solid particles in the atmosphere and equilibrates with other gases in the atmosphere. Carbon dioxide (CO_2), one of the gases present, dissolves in the water to produce carbonic acid (H_2CO_3). This weak acid ionizes only slightly to form some hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). At normal concentrations and pressures of CO_2 in the atmosphere the pH of rain is about 5.6 or slightly acidic. Other substances such as dust from the ground containing calcium (Ca^{++}), magnesium (Mg^{++}) and sodium ions (Na^+) and ammonium ions (NH_4^+) from organic decay also enter the atmosphere. They are slightly basic. Gases such as sulphur dioxide (SO_2) and hydrogen sulfide (H_2S) are produced by volcanoes and organic sources. When they are oxidized and hydrolyzed in the atmosphere they are converted to sulphuric acid. Similarly nitrogen oxides (NOx) are converted to nitric acid.

Natural precipitation is therefore dependent on the sum total of various substances in the atmosphere. On the prairies one would expect precipitation to be slightly basic (above pH 7) since dust in the atmosphere is a dominating aspect (20). On the other hand, over the Canadian Shield the precipitation is likely to be closer to pH 5.6 as the carbon dioxide effect would predominate. The pH of ice which fell as snow in Greenland about 180 years ago has a pH of 6.0 to 7.3 (42).

Since the Industrial Revolution began man has contributed more and more substances to the atmosphere. These substances include large quantities of sulphur and nitrogen oxides which originate in the combustion of fossil fuels and the smelting of sulfide ores. They tend to be converted by complex atmospheric processes to sulphuric and nitric acids and then fall to the ground as acid precipitation in rain or snow (Figure 1). Acid rain or acid precipitation is therefore defined as having a pH of less than 5.6 but is often in the range of 4.0 to 5.0. The lowest recorded pH of rain was 2.4 at Pitlochry, Scotland, on April 10, 1974, while the lowest annual precipitation pH is 3.78 in 1967 for De Bilt, Netherlands (42).

Figure 1
Schematic Representation of the Main Components of the Atmospheric Sulphur Budget from Synthetic Crude Oil Plants in a Northern Environment.


Worldwide background of SO_2 and sulphate aerosols
Background contribution of sulphate in rainout
Remaining SO_2 or sulphate aerosols added to general background
Oxidation of SO_2 and rainout
SO_2 enters cloud
Dry deposition of SO_2 and sulphate
Deposition of sulphate in precipitation
Emission of SO_2 from industrial plants

The History of Acid Rain

Eville Gorham (17, 19) was one of the earliest scientists to establish the occurrence of acid rain. He found that sulphuric acid from industrial regions was present in rain falling in the English Lake District. In the 1950's an international atmospheric network was set up in Europe. Svante Odén analyzed the data from this network and showed in 1967 that the acidity of precipitation had increased in most parts of Europe over a period up to 15 years (51). He found that the pH of precipitation dropped from 6.5 to 4.0 from 1955 to 1974 at some Scandinavian localities (50) which is an increase in acidity of about 300 times. However, the pH of annual rainfall in southeastern England, northwestern France and the Benelux countries was already 4.5 to 4.0 in 1956. This area was considerably enlarged by 1966 to include north Germany, Poland and southern Scandinavia, partially an effect of wind direction. Conditions stabilized during the 1970-1973 period (50).

The annual emissions of sulphur dioxide were estimated at 22 million tonnes from Western Europe in 1973 and 38 million tonnes for Eastern Europe while from 191[illegible]950 annual emissions in Europe were 25 million tonnes (57). Persson (57) also sug[illegible] that 25 million tonnes* per year of SO_2 would be the upper "tolerable" limit of emissions but should be less than that if the emission of nitrogen oxides are taken into account.

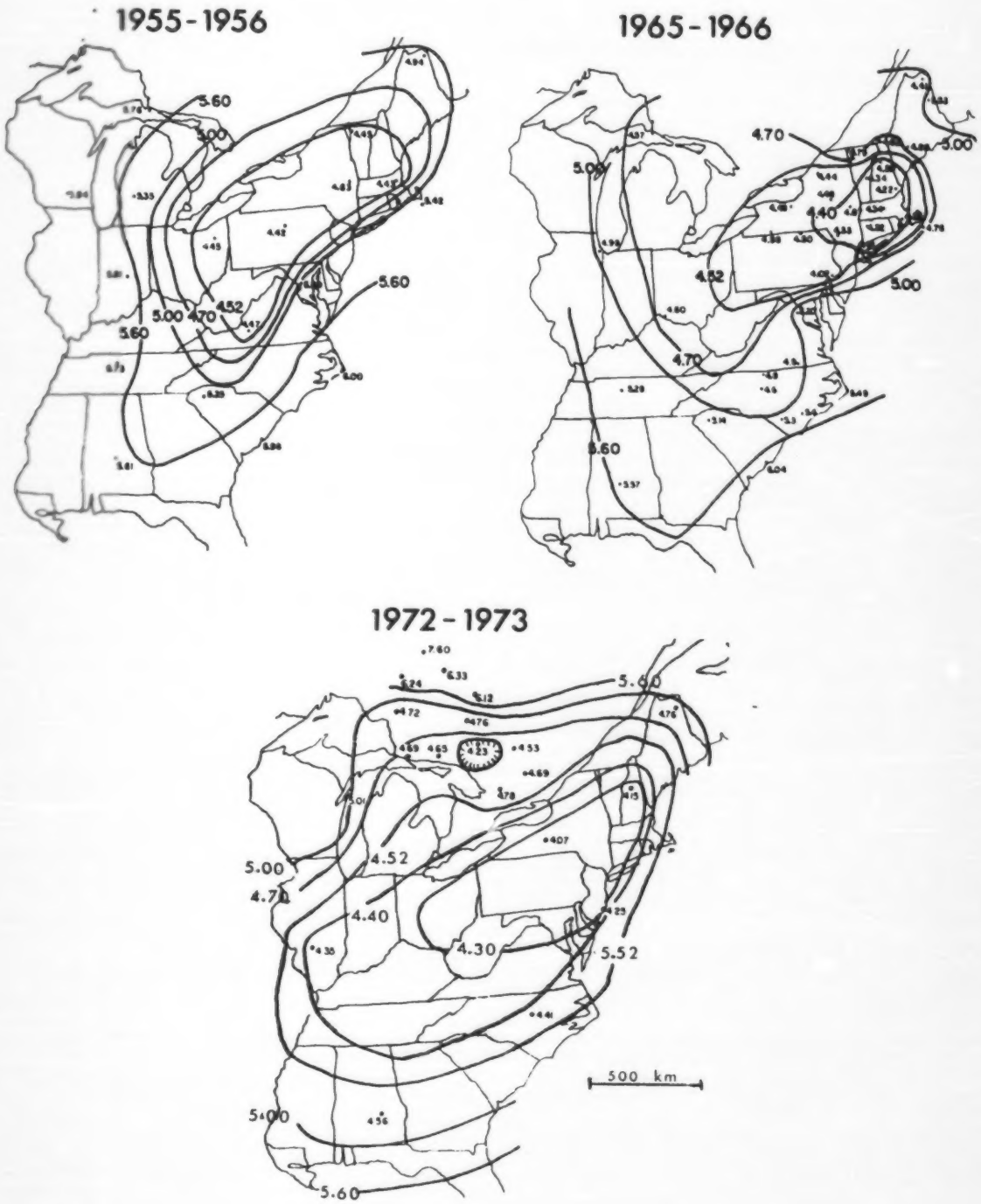
In North America, Gorham (18) first suggested that rainfall was the major source of sulphate which contributed to the lowered pH in some Nova Scotia lakes. Gorham and Gordon (22) showed that SO_2 emissions from the Sudbury smelting complex were responsible for the increased sulphate concentration and decreased pH in local lakes and vegetation damage. Likens and Bormann (41) suggest that the shift to natural gas from coal in home heating in New York State reduced the amounts of sulphur and increased the amount of NOx in precipitation during the period 1950-1955. Since then the increasing use of fossil fuels and emissions from higher stacks has dispersed SO_2 widely from urban industrial centers and produced 'regional acid rain' rather than local 'soot' problems. Annual mean pH at stations in the states of New York and New Hampshire in 1970-71 measured 3.91-4.03 while in industrial rainstorms pH was 3 to 4 (ibid).

Cogbill (9) illustrates the patterns of change in pH of precipitation during 1955-56 compared to 1965-66 and 1972-73 (Figure 2.). Acid precipitation occurred over a wide area of the eastern United States in the mid 1950's. The area of acid precipitation increased during the following ten years spreading west and south and intensifying in the New England area (ibid). Cogbill and Likens (10) calculated that 65% of the acidity was attributable to sulphuric acid and 30% to nitric acid. Cogbill (9) extended the 1972-73 pattern to include Canada although much of the area shown there would have received acid rain at the earlier times (Fig. 2). The 1972-73 pattern shows a further expansion and intensification of acid rain from 1965-66. Relatively low emissions occur over much of the rest of the United States although development of coal fields and shale oils in the west may change this picture. At present Great Plains (U.S.A.) coal development and utilization yield 2.5×10^6 t/yr SO_2 (16). The United States as a whole injects annually into the atmosphere 32×10^6 t/yr of anthropogenic (man-made) SO_2 and this may increase two to five times by the year 2000 (41). Fox (16) calculated that 24×10^6 t/yr of NOx are produced anthropogenically in the United States.

Table 1 shows the quantities and major sources of SOx and NOx emissions in Canada. The world's largest localized emissions of SO_2 (2.9×10^6 t/yr) occur in the Sudbury area but 85% of this is emitted from a single stack, the world's largest at 380 m (71). This is about 1% of the total world SO_2 emissions. The total for Canada was 6.17×10^6 tons/yr SO_2 in

*metric — tonnes (t); imperial — tons

Figure 2
The trends in pH of Acid Precipitation in Eastern North America at About Ten Year Intervals (from 9).



1974 (Table 1). The Canadian contribution is 5% of the world's anthropogenic SO_2 emissions (71). Most of the largest emitters are in Ontario but a few others are scattered across the country (see later). Ore processing produced 52% and utilities and power generation produced 23% of the sulphur emissions in 1974 (Table 1). Petroleum refining (4%), natural gas processing (13%), pulp and paper (2%), tar sands (2%) and transportation (2%) were other major contributors. The pH of the rainfall ranges from 4.0 to 5.0 in southern Ontario and the Great Lakes Basin (71), the lowest values in Canada. The second area of concern is Alberta where the developing oil and gas industry is steadily increasing emissions of both SOx and NOx (71).

Anthropogenic emissions of NOx in Canada are approximately one third those of SOx, i.e. 2.08×10^6 t/yr in 1974 (Table 1). Summers and Whelpdale (71) estimated that Canada contributed 2% of the world NOx emissions. Transportation contributes 64% of these emissions and utilities and power generation 24% while lesser amounts come from natural gas processing, petroleum refining and other industrial processes. The extensive use of large automobiles is a major contributor to the NOx emissions in North America.

Table 1

Canadian emissions (tons) of some air contaminants for 1974 (modified from Environment Canada 1978).

Sources	Sulphur* Oxides	% of Total	Nitrogen** Oxide	% of Total
Ore Processing	3,212,640	52.0	—	0.0
Pulp and Paper	117,821	1.9	15,892	0.8
Industrial Processes	180,701	2.9	38,592	1.8
Petroleum Refining	237,490	3.8	43,000	2.1
Natural Gas Processing	796,988	12.9	66,013	3.2
Tar Sands	96,000	1.6	—	0.0
Utilities and Power	1,438,667	23.3	503,916	24.2
Transportation	90,657	1.5	1,329,457	63.9
Miscellaneous	3,084	0.1	84,885	4.1
TOTAL	6,174,048	100	2,081,755	100

*expressed as tons of SO_2

**expressed as tons of NO_2

Long Range Transport of Atmospheric Pollutants

In 1950 smoke from Alberta forest fires appeared in Europe 8000 km away 5 days later (61). Atmospheric pollutants can obviously be transported long distances. Odén first presented the case in 1967 for long range atmospheric transport of sulphur dioxide which resulted in acid precipitation far from the origins of the emissions (51). Gorham (17, 19) was one of the first to propose that this occurred over a regional scale. Since then it has been well documented that industrial regions utilizing coal and oil with considerable sulphur content are the principal emitters and that oxidized components of these elements are transported long distances from the source.

Long range transport (over 100 km) patterns are determined by the dominance of major air mass types. The paths that these air masses in passing over major emitters will take determine which areas receive outfalls of pollutants. For example, southern Norway and western Sweden receive major acid rains where the pollutants are largely derived from England and other north European industrial areas. The pollutants tend to remain within 1 to 2 km of the surface of the earth (52).

Trajectories, tracing back the past movement of air masses, are used for assessing long range transport in western Europe (50, 52).

The pollutants may be directly dissolved in the rain or snow in its formation and then precipitated (rainout) or may be picked up by falling precipitation (washout) (16). In either case acid precipitation occurs. In less humid climates dry deposition of pollutants may predominate where the pollutants may fall out without mixing with water. If they contact water on the earth's surface, they will then form acid solutions if appropriate conditions exist or may become neutralized. In winter dry deposition will accumulate in the snow which may already be acid. During snowmelt a large amount of acid water is produced which may have major effects on the receiving water body (54).

Wet and dry fallout tend to decrease as distance from the source of emission decreases. Atmospheric behaviour affects fallout. Wind field, the temperature structure which determines the degree of mixing, and the forms of the water substance including its pH are important aspects involved (16). Near the source area precipitation tends to be highly acidic (near pH 4) but further away its occurrence is dependent on meteorological conditions (52). Mountain ranges which intercept air masses can lead to considerable (orographic) acid precipitation as is the case in southern Norway (ibid). Mountain ranges may also act as barriers to long range transportation while plains or seas will not impede transport. Odén (50) showed that the pH of acid precipitation increased (less acid) from pH 4.0 centered in the Netherlands — North Germany area to pH>6.0 in Northern Scandinavia and southern France and Spain in 1966.

Since present day requirements concerning pollution control are established on the basis of measuring fallout at various distances from the source of emission, industry has responded by building taller stacks (to reduce local effects), e.g. the 380 m stack at Sudbury. Emissions into the atmosphere at higher altitudes have reduced local fallout but increased long range transport. Acid precipitation may then occur 1000 km or more from the source. There has thus been a change from a local problem to a regional one to a continental and perhaps world-wide problem. Unfortunately the specific source of an emission producing acid rain is difficult to establish where a region has a number of large emitters and responsibility probably would have to be based on stack emissions.

Environmental Effects of Acid Precipitation

Deterioration of aquatic ecosystems has been the major stimulus for the investigation of acid rain and its prevention or reduction. Early investigators of acid precipitation were not aware of its deleterious effects (17, 18, 19). More recently Odén's (50) summation of the effects on ecosystems place the problem into true perspective.

Aquatic Ecosystems

Most investigations of effects of acid deposition have been directed at aquatic ecosystems since the effects are most obvious and most severe there.

The Chemico-physical Environment

The waters of lakes and streams have a broad spectrum of pH and ion concentrations. Bedrock and soils have a great influence on the composition of lake waters. Lakes most susceptible to acid rain occur in bedrock consisting of granites, gneisses and other hard rocks not easily weathered. Soils tend to be thin and acid podzols. These lakes have a low ionic composition. Typically pH in lakes of this type is in excess of 6.0. Their alkalinities are low and in the form of bicarbonates which exhibit a buffering action (preventing a rapid change in pH). These lakes are typical of those on the Canadian Precambrian Shield. Dickson (12) states that lakes with<0.1 meq/L (= 5 mg/L) natural alkalinity are most sensitive to acid precipitation. Thousands of Swedish lakes now fall into this category and ten thousand lakes have been acidified below pH 6.0 (ibid).

Any bicarbonate in precipitation is neutralized and exceeded by sulphuric and nitric acids from anthropogenic emissions. To be acidic rain must also have more sulphate ($SO_4^{=}$) and nitrate (NO_3^{-}) anions as compared to calcium (Ca^{++}) and magnesium (Mg^{++}) cations for example. The excess anions are then balanced by hydrogen ions (H^{+}) making rain acid. The excess strong acids in precipitation tend to neutralize bicarbonate already present in the lake waters. As a result the alkalinity decreases and a shift to a lower pH occurs. In eastern North America and Scandinavia poorly buffered lakes have decreased by 1 to 2 pH units (6.0 to < 5.0) and bicarbonate dominance has changed to sulphate dominance through sulphuric acid precipitation (77). Not only acid rain falling directly on lakes and rivers must be considered but also precipitation on lake drainage basins. The watershed too has an ability to neutralize acid rain but this ability is low if the drainage basin is composed of acidic granites and thin acid soils. Therefore the chemical conditions of surface waters reflect the reactions and changes of the soil system and bedrock of the watershed.

As acid precipitation continues thousands of lakes are threatened. Wright and Gjessing (77) state that 5,000 lakes in Sweden are seriously affected while another 5,000 lakes are in danger. In Ontario 140 lakes are in trouble and 48,000 more will be seriously affected over the next two decades unless a dramatic decrease in acid rain occurs (55). In some lakes in the La Cloche Mts., Ontario, acidity increased more than a hundredfold in one decade (4). Heavy metal concentrations may be greatly altered by lake acidification as their solubility is increased. Beamish (3) reported that concentrations of nickel, zinc, manganese and copper were higher than expected in the La Cloche Mts. Heavy metals may be toxic to fish. It has also been speculated that mercury may be solubilized and that high concentrations in fish in remote areas may be an effect.

Overrein (54) states "Acid precipitation affects the aquatic ecosystem in such a manner that it becomes controlled primarily by physico-chemical factors rather than by biological

mechanisms". Grahn and his group (23) conclude that continued acidification induces oligotrophication* and that this becomes a self-accelerating process through changes in biological populations.

Fish

Canadian and Scandinavian scientists have carried out most of the definitive research on the effects of acidic waters on fish. The general consensus is that as the pH of aquatic ecosystems decreases fish are selectively eliminated according to species.

Lumsden Lake, 65 km southwest of Sudbury, Ontario, declined from pH 6.8 to 4.4 during the decade 1961-1971 while some other lakes in the area suffered a similar change (5). Fish disappeared from the lake in the following order: burbot, lake trout, slimy sculpin, white suckers, lake herring and trout perch. This occurred over a five year period (1966-1971) and they attributed the change to increasing acidity. Lake chub was the only surviving species in 1971 (5). Harvey (26) found that the number of fish species in a lake correlated positively with pH, lake size, distance from the nearest and largest smelter and the number of zooplankton species.

In George Lake, Ontario, pH decreased 0.13 pH units a year and simultaneously lake trout, walleyes, burbot and small mouth bass disappeared. In 1973 (pH 5.2) northern pike, rock bass, pumpkinseed sunfish, brown bullhead and white suckers failed to reproduce (5). White suckers had spinal deformities and lowered concentrations of calcium in their blood serum which may have been related to inability to spawn (ibid).

Continuous failure of recruitment of brown trout in southern Norway in the most acidified region occurred and led to their reduction and extinction in many lakes during the 1960's (32). This followed the extinction of salmon and sea trout. Eggs, fry and young-of-the-year are most susceptible to acid water and this has a direct influence on recruitment (ibid). The percentage of lakes with no fish increased from 3.8 to 60% as the pH decreased from 5.5 to 4.0-4.5. Millbrink and Johansson (46) found that the lower pH limits of tolerance of fish roe were: roach 5.5; pike 5.0; perch 4.7.

Experimental work demonstrated that spermatogenesis of male flagfish was progressively reduced with decreasing pH down to pH 5.0 and volume of reproductive tissue was least at pH 4.5, the lowest pH water used (63).

Leivestad and Muniz (40) reported a massive fish kill (brown trout) in the Tovdal River, Norway, which they attributed to the sudden drop in pH (5.2 to as low as 4.0 in tributaries) resulting from snow melt. Deaths were attributed to the drop in plasma chloride (initiated by the lowered pH) and subsequent drop in plasma sodium.

Aquatic Plants

The increase in lake acidity (decrease of 1.4 to 1.7 pH units) in some Swedish lakes lead to a reduction of macrophytic plants (**Lobelia — Isoetes**) and these were replaced by **Sphagnum** moss which prefers low pH water (23). Filamentous algae also became more abundant on the lake bottom. The increasing amount of **Sphagnum** covered the sediment and prevented regeneration of nutrients to the lake water. Dense fungal growth also occurred on the bottom displacing normal bacterial populations. The decomposition rate was reduced and thus the rate of nutrient return was reduced. Both of these processes lead to oligotrophication (ibid) and thus a reduction in productivity.

*reduced production based on lower nutrients content

Phytoplankton are affected by increasing acidity. In Swedish lakes most of the diatoms and green algae disappeared below pH 5.8 (1) while below pH 5.0 only 10 species occurred, mostly pyrrophytes (flagellates). In lakes of the La Cloche Mts. near Sudbury, Kwiatkowski and Roff (38) found a reduction in both species and numbers of individuals as acidity increased. Lakes with pH 4.0-4.6 had less than one-third of the species occurring in lakes over pH 5.5. Primary production was only reduced below pH 4.4 (ibid).

Aquatic Invertebrates

Acidification of Swedish lakes lead to a reduction of zooplankton species (1). Most rotifers preferred pH>5.5 but two species appeared independent of pH down to 4.4 at least. Most cladocerans except for **Bosmina** preferred pH>6.0. Sprules (68) found that 64% of crustacean zooplankton species did not occur below pH 5.0 in La Cloche Mts. lakes and that 53% of the variation in zooplankton species was attributable to pH. In lakes with pH <5.0 one to seven species were present compared to a possible 28 species (ibid).

With regard to benthic (bottom) fauna the lowest number of species occurred in the most acidic lakes (23). In six Swedish lakes with pH < 5.5 no molluscs or mayflies occurred. Several insect groups (Trichoptera, Odonata, Hemiptera, Megaloptera) were most abundant in the most acid lakes (pH < 4.8) but water mites and crustaceans were absent below 5.0. Since many of these organisms are important as fish food, fish production would be reduced in lower pH waters.

Terrestrial Ecosystems

Large areas of the continents are occupied by forests or utilized as agricultural lands. Much of these lands are now exposed to acid precipitation. If any damage ensues economic returns are reduced. How susceptible are these regions?

Terrestrial ecosystems most susceptible to acid precipitation would be those exposed to high concentrations of acid fallout. Effects on soils and vegetation are most obvious in close proximity to high emissions (22). These effects may also be attributed to heavy metals and other pollutants in emissions. Probably more important is the mediating effect the terrestrial drainage area has on acid precipitation prior to runoff into surface waters. If it percolates rapidly through the soil, acidification of water is rapid (72).

Soils

Soils are complex systems composed of solid, colloidal, liquid and gaseous components in a continuous state of flux. Mineral and organic matter make up its solid component and the biological component (mainly bacteria and fungi) is intimately involved in its dynamic processes. Green plants derive many of their nutrients from the soil and restore organic matter to the soil.

Soils with an alkaline or neutral pH and a high proportion of basic cations (Ca^{++}, Mg^{++}, K^{+}, Na^{+}) are highly resistant to acidification. They have a high buffering capacity (72). These types of soils are characteristic of the glacial till cover of the Canadian prairies. They may also be associated with calcareous (limestone, dolomite) bedrocks.

Susceptible soils are those derived from and associated with non-calcareous crystalline rock such as granites and gneisses. These soils and rocks are low in Ca^{++}, K^{+}, and Na^{+}, are poorly buffered and usually nutrient poor (30). These soils tend to be acidic

podzols. Regions susceptible to acidification are the recently glaciated granitic regions of southern Norway and western Sweden and the Canadian Precambrian Shield of North America. Headwater areas are usually more susceptible than areas further downstream as buffering capacity has been reduced in the former and increased in the latter by leaching and redeposition respectively.

As the pH of soils is reduced, free metal ions tend to be released. Overrein (53) found that acidification leached calcium from podzolic forest soils and showed a sharp increase below pH 4. An associated effect is the rapid deterioration of limestone statues and buildings due to acid rain. Below pH 5.0 aluminum ions are mobilized and leached out of soils (20) and these can be toxic. Calcium, aluminum and magnesium concentrations have increased in Swedish rivers with the increase of hydrogen ions (45). Nutrients are leached out of the soils along with these major ions. Soils near Sudbury have pH's as low as 3 at a distance of 7.4 km (31) from the emission source.

Vegetation

The sensitivity of lichens to sulphur dioxide is well known and Hawksworth **et al.** (27) have attributed changes in lichen flora to this pollutant. Where the winter SO_2 levels are <30 $\mu g/m^3$, lichen floras are almost identical to late 19th century floras. As the SO_2 levels increased species became extinct locally and in Epping Forest near London only 28 of 118 species remain (ibid). Some species, particularly **Usnea** spp., are very sensitive to SO_2 while others tend to grow only where SO_2 exceeds a specific concentration (ibid). Lichens have been much reduced near Sudbury (31).

Gorham and Gordon (22) reported marked damage to vegetation near Sudbury. Observable damage extended to about 8 km from the smelters with damage increasing towards the emission source and most severe within 3.5 km. Hutchinson and Whitby (31) report an area of 250 km^2 around Sudbury devoid of vegetation while damage to the forest is obvious over an area of 5000 km^2. White pine **(Pinus strobus)** is most susceptible to SO_2 while deciduous red oak and red maple are more resistant (ibid). Alfalfa **(Medicago sativa)** and other plants show considerable sensitivity to SO_2 (34).

Knabe (34) describes sulphur dioxide as a primary toxicant to vegetation since it can pass through the stomata into the leaves. As the uptake of SO_2 is increased effects change from beneficial to steadily increasing damage. This damage can involve cell damage, destruction of chlorophyll and interference with enzyme activity (ibid). Effects on ecosystems depend on proximity to the emissions and subsequent economic use is directly related (Table 2). Nature conservation is most sensitive while crop production (including forests) is second in sensitivity. Ecosystem diversity changes with time as a result of SO_2 emissions. Knabe (34) states that acid precipitation is a secondary pollutant causing mainly indirect effects on vegetation.

Tamm and Cowling (73) provide an extensive list of specific direct and indirect effects on forest vegetation. These include cuticle damage, cell poisoning and interference with reproduction. Wet and dry fallout from the atmosphere are intercepted by the forest canopy. Hornbeck (29) found that 90% of the hydrogen ions (and therefore sulphate and nitrate ions) were filtered out by the forest canopy. During precipitation, throughfall in conifers has a pH of 3-3.5 (48). Although decreased forest production as an effect of acid precipitation has been inferred there is little concrete evidence since the effects are long term and variability of other environmental factors is considerable.

Both nitrogen and sulphur in acid precipitation may have a fertilizing effect as vegetation growth requires both elements. In good agricultural land the amount of nitrate applied as

Table 2

Local effects of SO_2 on socio-economic functions of vegetation (34).

Zone of damage	Degree of Disturbance to: Nature conservation	Crop production	Outdoor recreation	Filter capacity, avalanche control	Water protection, erosion control
Denuded zone	+ + +	+ + + all species	+ + +	+ + +	+ + +
Transition zone	+ + +	+ + + all species	+ + +	+ +	+ +
Grass and scrub zone	+ + +	+ + + all species	+ +	+ +	+
Zone of severe damage (acute leaf injury)	+ +	+ + esp. forest, garden, field	+ +	+ + no conifers	+ o
Zone of moderate damage (chronic leaf injury)	+ +	+ esp. conifers, soy beans	+	+ poor conifers	o
Zone of marginal effect	+ lichens	+ o	o	o	o

o effect insignificant
+ function slightly disturbed
+ + function substantially disturbed
+ + + function destroyed

fertilizer far exceeds that falling in acid rain. Noggle*, a soil chemist for the Tennessee Valley Authority (TVA), claimed that eliminating SO_2 from air pollution could cut farm production by 10% in seven states served by TVA.

Atmospheres containing SO_2 and associated pollutants are involved with altered respiration and increased lung disease in children, increased frequency and/or severity of asthma attacks and increased prevalence of chronic respiratory disease (8). Usually many pollutants tend to occur with oxides of sulphur but suspended sulphate appears to be more harmful than SO_2. Combinations of cations with sulphates tend to accentuate health problems. The whole area of effects of SO_2, sulphuric acid, sulphates and nitrates on human health requires reevaluation to determine dose response in man (ibid).

Atmospheric corrosion of metals (carbon steel, zinc and galvanized steel, nickel and nickel-plated steel) and painted steel and wood is significant (37). The SO_2 atmosphere of Stockholm had a corrosive rate six times that of rural areas. Sulphur dioxide, sulphates and acid precipitation have been directly correlated with the corrosion rate. In a Swedish study in 1970 it was estimated that the cost of corrosion by sulphur compounds in cities was $35 million per year. In the same year in the United States air pollutants caused $1.45 billion damage but the effects of sulphur pollutants have been substantially reduced since then (ibid). The long term damage of acid precipitation to limestone buildings and statues is well known.

*Saskatoon Star Phoenix, 1980, February 14, p. A6.

Nitrogen and sulphur oxides are major atmospheric contaminants in western Canada (Table 3). Of particular interest are the large emissions of SO_2 in Alberta by the oil and gas industry (93%)* and in Manitoba at Flin Flon and Thompson by ore processing (96%)*. Power generation using coal produces much smaller but similar amounts of SO_2 in each province. Transportation produces the largest amounts of nitrogen oxides (70% in Manitoba and Saskatchewan, and over 50% in Alberta) while power generation supplies the next highest proportion of the total emitted (14).

Table 3

Annual emissions (tons) of some air contaminants in Alberta, Manitoba and Saskatchewan, 1974 (from Environment Canada 1978).

Province	Sulphur oxides (as SO_2)	Nitrogen oxides (as NO_2)
Alberta	633,800	305,000
Manitoba	750,952	103,471
Saskatchewan	50,700	139,300

Figure 3 shows the distribution and relative emissions of sulphur from various sources in Alberta, Saskatchewan and Flin Flon, Manitoba. The latter is the single largest point source of SO_2 (280 t S/day) in the region and it is located on the Precambrian Shield near the Saskatchewan-Manitoba border. The next largest point source is the Suncor** oil sands plant at Fort McMurray (112.4 t S/day in 1978) (63). Emitters of between 50 and 100 tonnes/day are the power generating plant near Estevan, Saskatchewan, and the gas processing plant near Rocky Mountain House, Alberta. A great number of small sulphur emitters, principally associated with gas processing, are located mostly in the western half of Alberta. Table 4 gives the sulphur emissions in Alberta in 1978 for each industry.

The gas plants produce the most sulphur emissions (56%) but they tend to be widely scattered (Figure 3) and, for the most part, each plant has relatively low emissions. The sulphur originates in natural gas and most of it is extracted and stockpiled as solid sulphur. Some is lost as atmospheric emission. The oil sands plants emitted almost 20% of the sulphur lost to the atmosphere in Alberta in 1978. Suncor utilizes coke (6% sulphur content) (65) as fuel and most of its sulphur emissions originate in the power plant. Smaller amounts are produced in its sulphur plant and in the burning of hydrogen sulphide (flaring). Oils as well as natural gas contains sulphur and may contain hydrogen sulphide (sour gas).

Substantial progress has been made in reducing sulphur emissions in the extraction of synthetic crude oil from the oil sands. Sandhu (65) states that emissions changed from 13 t S/1000 m^3 of bitumen processed by the first oil sands plant (Suncor) to 4.8 t S/1000 m^3 in the second (Syncrude) to 1.2 to 2.4 t S/1000 m^3 bitumen for proposed plants.

The Alberta Environment target is 1.0 tonne SO_2 / 1000 barrels of synthetic crude and it is hoped that this target will be met by 1985-86. However, requirements for new plants are

*percentages of total emissions in each province

**formerly Great Canadian Oil Sands

Figure 3

The Distribution of Sulphur Emissions (tonnes / day), Present (1978) and Projected (2000), according to Industry Source (from 64, 71, 39, 13). (*projected emissions).

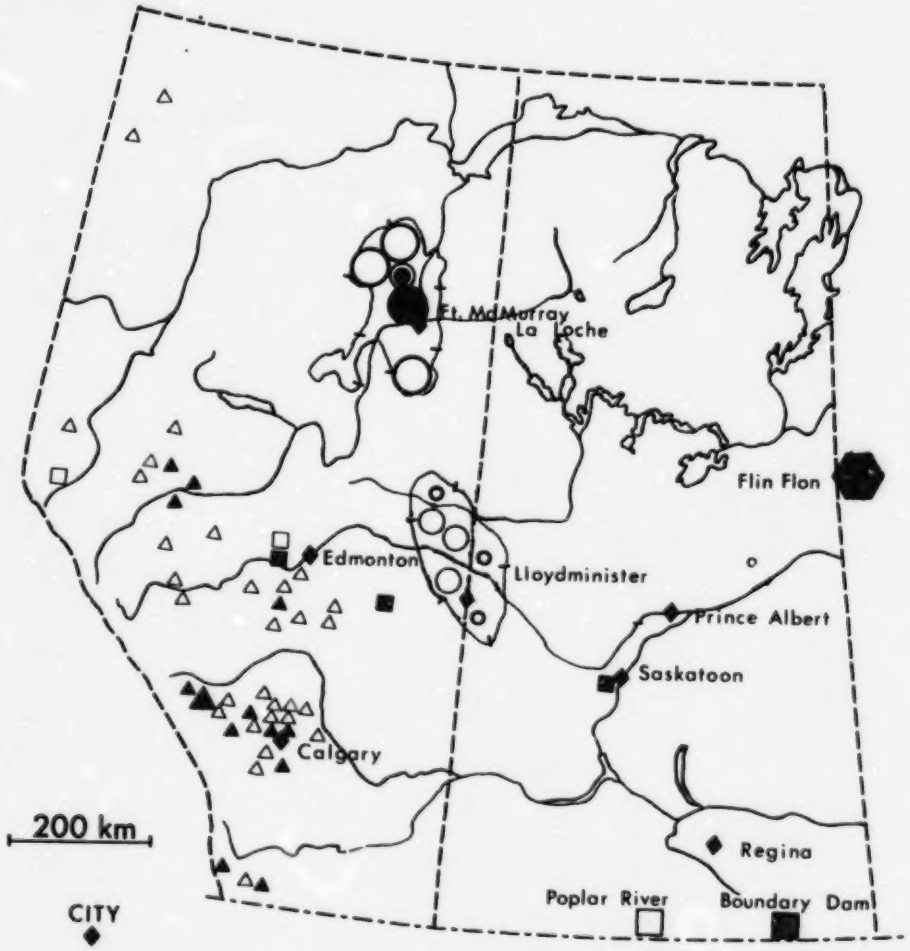


Table 4

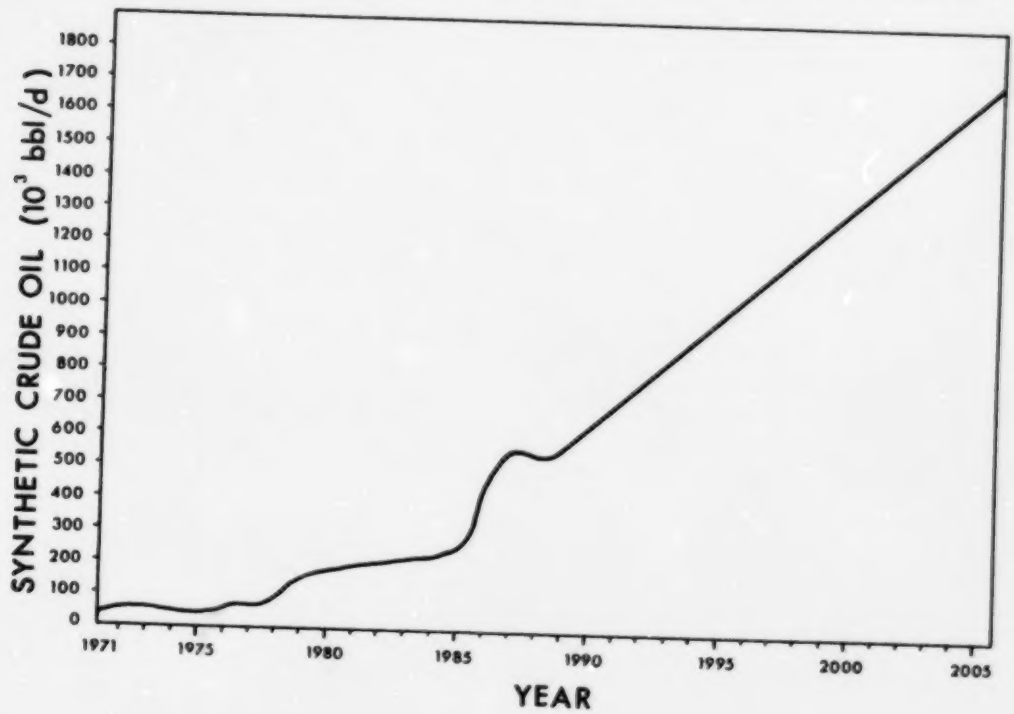
Observed sulphur emissions* from industries operating in Alberta in 1978. The number of plants is given in parentheses. (Modified from Sandhu 1979).

Source	Tonnes/day	% of total
Extraction gas plants	422.2 (43)	56.0
Oil sands plants	147.4 (2)	19.6
Sour oil production	54.7 (324)	7.3
Power plants	48.0 (4)	6.4
Flaring gas plants	24.6 (28)	3.3
Refineries	21.8 (5)	2.9
Pulp and Paper	18.7 (5)	2.5
Fertilizer plants	10.3 (5)	1.4
Other	6.0 (2)	0.8
	753.7 (415)	100.2

*In terms of SO_2 these values would be twice as great.

Figure 4

Synthetic crude oil production in Alberta including projections to 2006 (data from E.R.C.B. 1978).



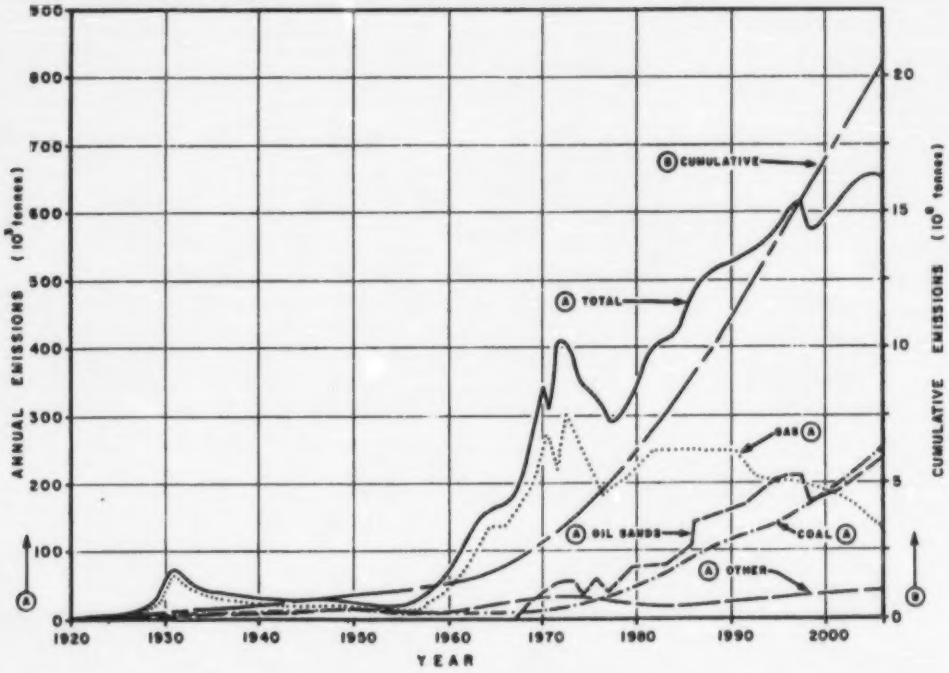
that they utilize coal for fuel rather than natural gas and that Alberta Environment will only require 90% sulphur removal. This would lead to much higher emissions over the next two decades (74).

The Alberta Energy Conservation Board (13) projected future energy requirements in Alberta and postulated several scenarios of increased production. Figure 4 illustrates a rapid development phase in the production of synthetic crude. Suncor and the expanded Syncrude plant would reach full production of 260,000 bbls/day in 1985-86. A third mining plant (Alsands) would be in operation in 1986 at 125,000 bbls/day. Beyond 1987 new plants would come on stream every 3-4 years alternating between **in situ** and mining operations. Each of these would produce 210,000 bbls/day. The minimum development scenario foresees the third mining venture postponed until 1990 and the first **in situ** plant operable in 1992 with new plants appearing at 5-year intervals thereafter.

They also forecast that ten million tons of subbituminous coal a year would be needed to supply fuel for the **in situ** oil sands plants by 2006. Figure 3 illustrates the projected four **in situ** plants in the Cold Lake-Lloydminster region if development proceeded rapidly as outlined above. Together with four more mining oil sands plants at Fort McMurray these would ultimately emit 1,720 t SO_2/day by the year 2006 if the Alberta Environment target of 1.0 t SO_2/1,000 bbls synthetic crude is achieved (Fig. 4). On the other hand if the use of more coal precludes this target, sulphur emissions would probably be double this amount. The Board also projects three petrochemical plants with the first operating in 1984 and others going on stream at 8 year intervals. Each plant would require 850,000 tonnes of coal per year. The projected total utilization of coal for energy production in the year 2006 is 47.6 million tons (ibid). This coal is all subbituminous and contains a considerable amount of sulphur. An associated problem is the large amount of sulphur removed from emissions

Figure 5

Annual and cumulative sulphur emissions from energy industries in Alberta, 1920 to 2006 (from 65).



and stockpiled, e.g., 1050 t S/day at the projected Imperial Cold Lake **in situ** plant (15). However, environmental problems associated with stockpiles are local only.

Figure 5 illustrates the annual changes in sulphur emissions from energy industries in Alberta. The predicted decline in natural gas production after 1990 is associated with a decline in sulphur emissions. An irregular increase in sulphur emissions from oils sands plants and a regular increase from coal is predicted. If the sulphur emissions are about 350,000 tonnes in 1980, these emissions will almost double to 650,000 tonnes in 2006. Cumulative emissions are projected as 21 million tonnes, more than four times the accumulation by 1980. (In terms of SO_2 these values would be twice as great).

Alberta air quality standards permit a maximum annual average of 30 μg SO_2/m^3 and a maximum of 525 μg SO_2/m^3 for 0.5 hour average. Federal air quality objectives permit a maximum annual concentration of twice the Alberta standard but the same level as Alberta's is designated as desirable.

Deposition of Emissions

The Alberta Oil Sands Environmental Research Program (67) found that concentrations of SO_2 in the atmosphere ranged from 0.001 to 0.341 ppm at 3 km from the Great Canadian Oil Sands plant (now Suncor), near Fort McMurray, with the lowest value occurring 44 to 96% of the time depending on the month. Barrie and Kovalick (78) concluded that only 0.3 to 2% of the total sulphur and nitrogen oxides were deposited in the snow pack within 25 km of Suncor while at least 98% was transported beyond 25 km.

At La Loche, Saskatchewan, (125 km east of Fort McMurray), Shewchuk (66) found atmospheric concentrations ranging from non-detectable to 18.1 μg SO_2/m^3. Back trajectories indicated that the high SO_2 levels of July-August, 1978, could be traced back to the oil sands region. The highest particulate (SO_4) concentrations (>1 μg S/m^3) occurred in the winter (December-March) and this was attributed to channeling of air masses by the Clearwater River valley (ibid). This phenomenon has also been demonstrated in the Athabasca River valley particularly during winter inversions (67).

Nyborg and his colleagues (49) studied the effect of fallout at 93 monitoring stations in Alberta and western Saskatchewan. In the spring of 1974 near Fort McMurray deposition of sulphate sulphur in snow varied from 0.18 to 0.60 kg/ha while snow pH varied from 4.7 to 5.4 depending on the direction and distance from the oil sands plant which emitted 140 t S/day. Concentrations were often greatest at more remote stations (10, 55 km) rather than close to (2.5 to 5.0 km) the plant. The total winter accumulation 5 km from the plant was 1 kg S/ha (ibid).

Shewchuk (66) studied sulphur deposition near La Loche, Saskatchewan, in 1977-78. Mean sulphur deposition in the snow pack was 0.09 mg S/m^2/day or 0.1 kg/ha for the winter (120 days). The pH of a snowfall was 4.8 on February 23, 1978. A site at Canwood, Saskatchewan (47), 450 km from the oil sands plant near Fort McMurray contained 0.1 kg SO_4-S/ha in snow pack while the snow pH was 5.0 (49).

Near a large gas processing plant (84 t S emissions/day) in the forest zone, sulphur appeared in the snow pack within a similar range as near the oil sands plant (ibid).

Rain, at various locations in Alberta, contained five times the sulphur concentrations of snowfall (ibid). Sulphate sulphur concentrations varied from 1.4 to 2.7 ppm or 1.5 to 1.9 kg/ha over three months, June, July and August 1973. This was two to three times as great

as the sulphur in precipitation at a station remote from the emission source. The high sulphate sulphur concentrations are sufficient to lower pure water to a pH of 3 to 4 but since the atmosphere is high in cations (49) and alkaline buffering originating in dust, smoke and other atmospheric pollutants (67), pH values ranged from 5.5. to 6.7.

Summers and Hitchon (70) analyzed the sulphate content of summer rains (1967-1970), fresh snow (1969) and hail (1969) in central Alberta. Figure 6 illustrates the variations in sulphate sulphur for various precipitation episodes. Rain contained the highest concentrations of sulphate averaging 2.7 mg/L (0.9 mg S/L) with values as high as 12 mg SO_4/L (4 mg S/L). Snow contained the least, i.e. an average of 0.6 mg SO_4/L (0.2 mg S/L). The liquid water content of snow producing clouds in winter is one-tenth that of rain clouds in summer. This reduces the SO_2 scavenging efficiency of snow especially in very cold climates. In addition the presence of ice crystals slows the rate of oxidation of SO_2 decreasing the amount of sulphate present in snow (ibid). Hail sulphate concentrations averaged 2.9 mg/L (0.93 mg S/L) in central Alberta, very similar to that of rain. Summers and Hitchon (70) calculated that 25 cm of rain in June, July and August deposited 2.5 kg SO_4/ha (0.83 kg S/ha). They determined that 32 to 46% of the SO_2 emitted was deposited by convective storms in the summer within a 25 km radius of the emission source while <2% of the emissions were deposited by snowfall that close to the source. This situation is peculiar to the location of the gas plants near and in the Rocky Mountain foothills (ibid).

Shewchuk (66) found that sulphate concentration in precipitation was 1.1 mg/L (0.37 mg S/L) during February at La Loche and ranged from 0.83 to 1.25 mg/L (0:28 to 0.42 mg S/L) during June to October 1978. The pH range was 5.42 to 5.98.

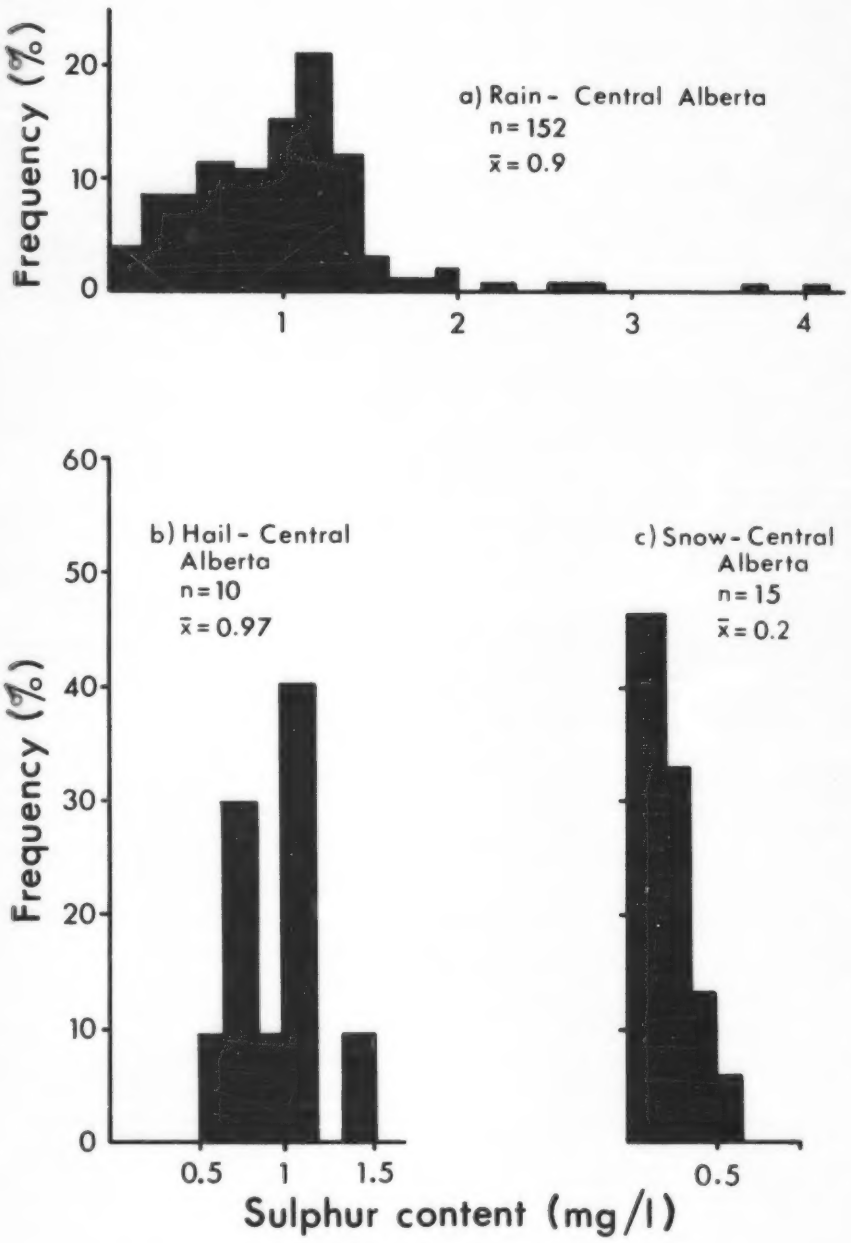
Rain became strongly acid when intercepted by forest trees. Deposition was 2.6 kg SO_4—S/ha/month at control sites. Dry deposited sulphur is apparently washed off the tree canopy during rainfall (49). The pH of this throughfall is frequently between 3 and 3.5 (48).

Nyborg (49) determined that rain and snow combined deposited 4 to 5 kg/ha sulphur annually near emission sources and 1 to 2 kg S/ha/year in areas remote from their sources in Alberta. These amounts are insignificant when compared to the total daily emissions of gaseous sulphur in Alberta (ibid).

Nyborg (49) calculated that the amount of SO_4-S gained by the soil from dry deposition was 10 times that detected in rainfall. Within 11 km of a gas plant soils gained 3.8 to 20.1 kg SO_4-S/ha. Dry particulate sulphur fallout averaged 0.32 kg/ha/week in Central Alberta but little or none (0.00 - 0.023 kg/ha/week) at sites remote from emission sources, i.e., western Saskatchewan. It was also found that absorption of sulphur under a closed canopy was 4-15 kg/ha in 6 months, far more than the amount deposited by rainfall (ibid).

Nyborg (49) estimated that as much as 50 kg SO_4—S/ha is deposited 20 to 30 km downwind from large single emission sources while annual deposition in Alberta by rain and snow is not more than 4 kg/ha. During the winter most of the SO_2 emissions drift out of Alberta (ibid). High atmospheric concentrations found in the summer at La Loche, Saskatchewan, by Shewchuk (66), indicates that this also occurs at other times of the year. Precipitation wherever it occurs will result in rainout and washout of SO_2 in the atmosphere at specific locations. Summers and Hitchon (70) concluded that most precipitation of sulphur occurred through rainout in central Alberta so that this probably also happens in Saskatchewan. Sandhu (65) cites a study where the total fallout of SO_4—S (in snow, rain and dustfall) averaged 2.2 kg/ha/year but this was only 15% of the annual S emissions.

Figure 6
Variations in Sulphate Sulphur content of Various Precipitation Episodes in central Alberta, 1969 (modified from 70). (n = number of samples, $\bar{x}$ = mean value).



Environmental Effects

Soils

Total sulphur content of surface soils increases from brown through dark brown to black types but decreases in dark grey and northern grey soils (65). The grey soils tend to be sulphur deficient but this may also occur in other soils particularly when heavy nitrogen fertilizer applications are made (ibid). Grey soils may be naturally acidic, e.g. 31% of the Peace River region soils have pH<6.0. Further damage to soil quality would occur when sulphur is added to these soils (ibid).

The pH of soils (0 to 12 cm deep) under closed canopies downwind from a gas processing plant in southern Alberta was depressed more than 0.15 pH units in a three month period (49). A depression of 0.15 pH units occurred within a 25,000 km^2 area in central Alberta where half the sulphur emissions were upwind of the study area. It was found that pH depression was twice as great on prairie soils as on western forest soils, i.e., from 5.64 to 5.45 and to 5.54 respectively (ibid).

In an experiment with different types of natural substrate, soils gained 8 to 9 ppm* SO_4-S while their pHs decreased more than 0.1 unit when exposed to 24 ppb* SO_2 for 30 days. Spruce bark and forest litter gained 30 to 36 ppm SO_4-S in a similar experiment. **Sphagnum** moss gained 50 ppm SO_4-S while exposed near an oil sands plant for 8 weeks as compared to control sites (ibid). Fine textured and wet soils absorb relatively more SO_2 (65).

Soil acidification is a long term effect of SO_2 emission and it is cumulative. If 50 kg S/ha is deposited annually, pH could drop 0.5 to 1.5 pH units in the top 15 cm of soil over a 10 to 20 year period (49). This takes into consideration the buffering capacity of Alberta soils. Sandhu (65) cites a study which identifies highly calcareous soils as most resistant to acidification while acidic sandy soils are most sensitive.

However, what isn't known is the proportion of emitted S which is deposited as sulphuric acid as compared to the neutral salts. If SO_2 is absorbed by the soil, it is converted to sulphate. In both cases sulphate may be converted to other forms of sulphur which remain in the soil or are used by crops. Conversion to other forms would reduce the rate of acidification or even prevent it. If acidification accumulates, soils will tend to remain acidic even after SO_2 emissions cease and can only be returned to their original pH by the addition of lime. This approach is used widely in eastern North America and elsewhere to decrease acidity. Nyborg (48) predicts that liming will be required within a decade or so for agricultural soils which occur near SO_2 emission sources. It may be practical to lime forests as well. Of related importance is the acidifying effect of nitrogen fertilizer applied at the recommended rate. It has been estimated that this will increase acidification four-fold over the next 20 years unless liming is practiced (56). The effects of sulphur emissions can be added to this factor.

Vegetation

Limited research on the effects of sulphur on vegetation has been carried out in Alberta and has confirmed the effects determined elsewhere (65). Large areas of Alberta have sulphur deficient soils but emission sources cannot be relied upon to overcome deficiencies because of 'variability in forms, amounts and timing of depositions' (ibid). Many soils in Alberta, in contrast, are high in sulphur and luxury consumption by plants of the element occurs without apparent ill effects to the plants. Excess sulphur is accumulated as sulphate in the straw of crops (ibid).

*(ppm = parts per million; ppb = parts per billion)

No studies show any direct effect of SO_2 on crops. Experimental work has shown that injury to plants is greater when relative humidity is high and available nitrogen is low. Other factors affecting plant tolerance to SO_2 include light intensity, temperature, water on leaves, maturity of plants or plant parts, vigor of plants and genetic factors (65). Buffering by crop vegetation does not play a significant role in agricultural systems as is the case in forests (ibid).

Crop damage is more likely to be indirect through effects of soil acidity. Under field conditions the tolerance of crops to acidity is as follows: red clover > rape = Olli barley > Galt barley > alfalfa. A decrease of 1 pH unit would prevent growing barley on many Alberta soils. In the range of pH 5.2 to 5.5, a drop of 0.1 pH unit reduced barley yield 161 kg/ha (3 bu/acre) while in the range of pH 5.5 to 6.0, a similar pH decrease reduced alfalfa yield 448 kg/ha (400 lb/acre) (56). These authors conclude that soil acidity reduces crop yield by $14.5 million each year in Alberta. Nodulation of alfalfa was reduced by soil pH below 5.6 while in red clover it was reduced below pH 5.0. These results were reported by various investigators cited by Sandhu (65).

Selenium deficiencies of soil occur in the zone between Calgary and Edmonton and west to the Rocky Mountains in Alberta (36). If sulphur is abundant it competes successfully with selenium for absorption by plant roots and thus plants contain little selenium. This problem is accentuated if the region is also sulphur deficient as sulphur added stimulates the growth of plants and relatively even less selenium is accumulated (ibid). At low pH selenium may not be available as it forms complexes with heavy metals (65).

It has been suggested that sulphur emissions are potentially more harmful to forest vegetation than to agricultural crops. Sensitivity of some forest species to SO_2 on an experimental basis has been determined. Highly sensitive species* are balsam poplar (**Populus balsamifera L.**), green alder (**Alnus crispa** (Ait.) Pursh.), white birch (**Betula papyrifera** Marsh) and tamarack (**Larix occidentalis** Nutt.) while trembling aspen (**Populus tremuloides** Michx.) and jack pine (**Pinus banksiana** Lamb.) are moderately sensitive. White and black spruce are relatively resistant to damage (44). Herbs and shrubs also show various degrees of sensitivity to SO_2. High experimental applications of SO_2 result in chlorosis (yellowing) of conifer needles and interveinal chlorosis of broadleaf plants. Reduction of growth and yield are physiological responses (ibid). After three years of observation of selected jack pine stands in the Alberta oil sands region (1976-1979) there is no observed damage to vegetation there (ibid).

Changes of plant species and soil parameters can be used in a monitoring program to deduce the individual effects of SO_2 emissions. A lichen network has been suggested as the best early warning monitor of industry pollutant emissions. In Alberta lichen species **Parmelia sulcata** and **Hypogymnia physodes** are being used for this purpose while species of **Usnea** are also present (43). However, the impact on a whole ecosystem and its response cannot easily be measured.

Human and Other Animal Populations

Little evidence exists regarding ill health in humans caused by industrial emissions of SO_2 in Alberta. Experimental exposures, however, indicate that SO_2 can cause adverse health effects but concentrations required to produce these effects are high relative to levels actually encountered in the Alberta environment. A more serious health hazard is H_2S which was involved in 221 cases of poisoning with a mortality of 6% during 1969-1973 in Alberta (literature cited in 65).

*These species are common to northern Saskatchewan.

No direct long term effects of SO_2 emissions on cattle, hogs and chickens were noted in spite of the firm belief of the agricultural community to the contrary. Experimental exposure of pigs produced adverse effects but the concentrations were much higher than found naturally (ibid).

A selenium deficient diet (magnified by the presence of increased sulphur) is the cause of white muscle disease which affects cattle, sheep, horses, swine, chickens and turkeys. This disease involves the degeneration of muscle and affects growth. Tongue muscles of calves don't function properly and calves die. Infertility is also an effect. In addition the ingestion of sulphur in feed interferes with the digestion of food in the rumen (by micro-organisms) and the uptake of food by the intestine and the cells. As in plant roots sulphur has a competitive advantage at these sites and less selenium is utilized by the animal (36). Selenium injections and diet supplements can be used to treat and prevent this disease. However, when the actual fallout of sulphur emissions is unknown the proper dosage is difficult to determine. Too much selenium is toxic (ibid).

Corrosion

The rate of corrosion of metals is increased with increasing proximity to sour gas wells (65).

Water

Hesslein (28) found that lakes in the Alberta oil sands region have high alkalinities and therefore high resistance to pH change. The most susceptible lakes are in the Birch Mountain area 50 km northwest of the nearest oil sands plant. However, he concluded that for these lakes to be affected rainfall pH must be below 4.0 which he considered unlikely. He calculated that sulphur emissions from the oil sands area would be about 25% of the Sudbury area by 1985 but he did not make projections beyond that date.

Taylor (74) is, however, much more concerned for the potential of acidification of lakes to the west and northwest (of the oil sands plants) and northeast where outcrops of Pre-cambrian Shield occur. He proposes that the bulk of the potentially sensitive areas are located in northern Saskatchewan and southern Northwest Territories where much more susceptible ecosystems occur.

Saskatchewan surface waters overlie a broad spectrum of rock and soil substrates. The northern third of the province is Precambrian in origin (Fig. 7) and is underlain by metamorphosed granites and gneisses and unmetamorphosed sedimentary rock which occurs particularly as the Athabasca Formation south of Lake Athabasca. Rock outcrops are common or the bedrock may be thinly covered with acidic podzols, organic fibrisols or sands (62). Mineral concentration of lake waters tend to reflect the nature and solubility of drainage substrate materials. Indicative of the low solubility of the substrate is the low concentration of dissolved minerals in lake waters (Table 5). Lakes of the entire Precambrian Shield in Saskatchewan have < 100 mg/L but most of them have < 50 mg/L total dissolved solids (2). Associated are the very low alkalinity and calcium concentrations (Table 5) which provide a low buffering capacity. The pH ranges from 6.0 to over 7.0 in this region (Table 5). The northern Boreal forest covers most of this part of the province.

Paleozoic rocks outcrop and underlie the Cumberland Lowlands (Figure 7). These rocks and their derivatives are rich in calcium carbonate (limestone, dolomite). A similar situation occurs in the Cluff Lake anomaly located within the Athabasca Formation. Soils tend to be organic fibrisols or poorly drained gleysols (62). Lakes have higher total dissolved solids and alkalinity and pH, e.g., Cluff Lake (Table 5), and thus have a higher buffering capacity.

The remainder of Saskatchewan is sedimentary rock covered to an average depth of 60 m with glacial till and outwash materials (25). Relief is generally low and lakes tend to be

Table 5

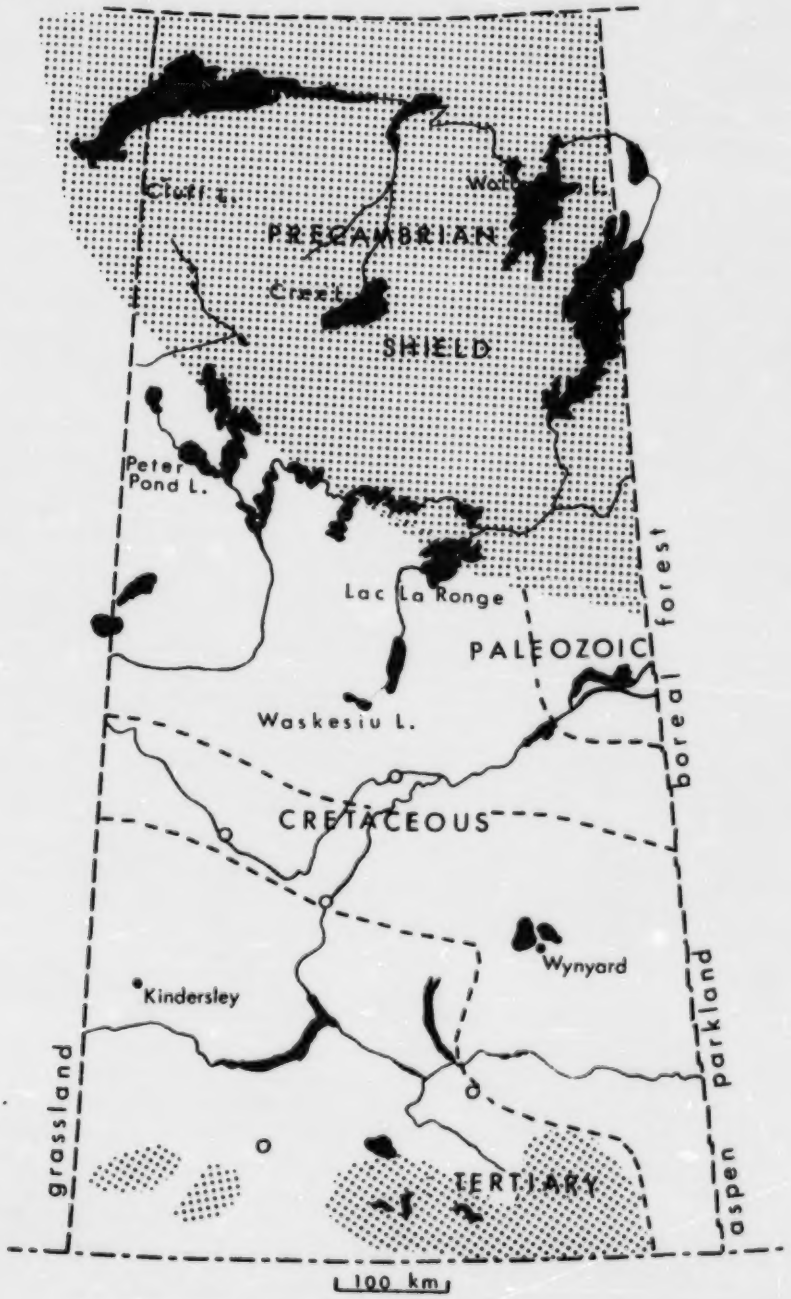
Chemical data for waters of some northern Saskatchewan lakes. Sampling dates were in August except for Cluff, La Ronge and Wollaston lakes which were in June.

Region and Lake	TDS* (Sp. Cond**)		pH	Alkalinity	HCO_3^-	$CO_3^=$	$SO_4^=$	Cl^-	Ca^{++}	Mg^{++}	Na^+	K^+	CSI***
Precambrian													
Cree Lake region													
Cree (60)	22		6.80	20.0	24.6	0.0	0.6	0.40	2.60	1.00	2.8	—	2.78
Key (33)	25	(16.2)	7.13	7.5	9.5	0.0	<1.0	0.10	0.65	0.37	1.2	0.1	3.47
McDonald (33)	16	(13.8)	6.92	5.9	7.2	0.0	<1.0	0.27	0.61	0.34	0.9	0.1	3.83
Seahorse (33)	16	(12)	6.80	5.1	6.2	0.0	<1.0	0.15	0.45	0.33	0.9	0.2	4.14
Cluff (75)	91	(126)	7.88	61.0	31.0	0.0	<1.0	4.50	5.80	4.00	1.9	0.7	0.87
La Ronge Region													
Contact (35)	55		7.00	20.0	35.0	0.0	3.0	10.0	8.0	5.0	1.8	1.7	2.10
McKay (35)	60		7.10	17.0	29.0	0.0	2.0	14.0	5.8	1.6	2.2	0.8	2.21
Wollaston (60)	40		7.20	19.0	23.6	0.0	0.6	0.0	3.6	7.5	0.4	—	2.26
Cretaceous													
Peter Pond (59)	136		8.20	107.0	131.0	0.6	5.7	2.5	26.7	13.5	0.7	—	−0.35
La Ronge (2)	134		8.20	105.0	123.9	4.9	2.7	0.0	27.0	8.5	3.6	—	−0.35
Waskesiu (59)	181		8.40	147.3	179.6	0.0	3.1	6.0	35.0	14.1	←15.1→		−0.81

*TDS (total dissolved solids). Alkalinity as $CaCO_3$ and all ions in mg/L.
**Sp. Cond. (specify conductivity in µS/cm at 25°C).
***CSI — calcite saturation index.

much less numerous than on the Canadian Shield. Soils tend to be gray wooded, podzolic, regosolic and organic in the southern Boreal Forest immediately south of the Shield to about 53° N Latitude. The Aspen Parkland (Figure 7) is a transition zone located between the boreal forest and the grasslands. The soils tend to be black. The Grassland region in

Figure 7
Geological and Vegetational Zonation of Saskatchewan.



the south is covered with dark brown and brown soils. Since the solubility of the substrates in the drainage basins of the lakes is much higher, total dissolved solids content and ion concentrations are also higher (Table 5). Even lakes on the margin (Lac La Ronge) or just off the Shield (Peter Pond) have considerably higher concentrations since their drainage is derived from off the Shield (Table 5). Total dissolved solids generally range from 100 to 200 mg/L in lakes of the southern boreal forest and from 200 to 500 mg/L in the aspen parkland. The pH values vary from 6.5 to 9.4 in the former to 6.8 to 10.0 in the latter although most values are closer to pH 8.0 (2). In southern Saskatchewan large endorheic (interior) drainage basins (no outflow) occur and their lakes tend to be saline. Total dissolved solids often range from 3000 mg/L to almost 400,000 mg/L (24). These lakes usually have pH ranges of 7.9 to 9.6 and have high alkalinities (ibid). All lakes south of the Canadian Shield tend to be well buffered since their alkalinity and base cation concentrations are relatively high and these generally increase from north to south.

Tertiary bedrocks occur in southern Saskatchewan in the Wood Mountain and Cypress Hills regions. Lakes are relatively few in number and often small. Although their water quality is sometimes better than lakes located in the Cretaceous region they are still well buffered.

Sulphur deficiencies occur in Saskatchewan gray-wooded soils and are becoming more obvious in black soils. Some indication of deficiencies have recently appeared on dark brown soils (Indian Head) and even in brown soils. Rape and alfalfa crops are particularly heavy users of sulphur (69).

Selenium deficiencies have been reported north of an east-west line through Rosetown; i.e., the northern agricultural zone. White muscle disease occurs in cattle, sheep and horses. In the southwest selenium reaches toxic levels by accumulating in plants such as **Astragulus** (locoweed). Sulphur interferes with the uptake of selenium by plants but also interferes with the uptake of copper and zinc. Diet supplements may be required for copper and zinc as well as for selenium (7).

Acid soils (pH 6.0 or lower) occur in west central Saskatchewan and extend north to Meadow Lake and Loon Lake (76). Soils in the vicinity of Kerrobert, Wilkie and Unity have pH of about 6.0 while areas near Scott are down to 5.0. The decrease in pH is the result of leaching out of base ions (76).

Susceptibility of Lakes to Acidification

The calcite saturation index (CSI) has been developed (11) to provide a method of assessing lake sensitivity to the addition of acids. The logarithm of the degree of saturation of a water body by $CaCO_3$ is:

$$CSI = p(Ca^{++}) + p(Alk) - (p(H^{+}) + pK$$

where $p(X) = -\log_{10}(X)$, $pK = +2$, (Ca^{++}) in mol/L, and (Alk) and (H^{+}) in eq/L

Derived indices are indicative of specific acid deposition sensitivities: CSI < O, supersaturated with $CaCO_3$, not sensitive; CSI < 1, unlikely to be affected; CSI = 1 - 2, slightly sensitive: CSI = 2 - 3, in danger; CSI > 3, acid loading will be deleterious (21).

Table 5 shows the variability of some northern Saskatchewan lakes with respect to pH, alkalinity, calcium and various other ions and the CSI index. Typically on the Shield the chemical concentrations are relatively low with the lowest values occurring in lakes in the vicinity of Cree Lake (Athabasca Formation) and slightly higher values in the La Ronge and Wollaston regions. All of these lakes are in danger with respect to acidification while the Key Lake area lakes (Key, McDonald, Seahorse) are in greatest danger (CSI > 3) (Table 5). These lakes typify the sensitivity of Shield lakes.

Lakes in calcareous regions including Cluff Lake are unlikely to be affected as the CSI in the case of Cluff Lake is < 1. Lakes off the Shield, Peter Pond, La Ronge and Waskesiu, are supersaturated with $CaCO_3$ and have CSI indices < 0 (Table 5). These lakes are therefore all too well buffered to be affected by acid deposition. These lakes are typical of almost all lakes south of the Precambrian Shield.

The rate of acidification of a lake depends not only on its buffering capacity but on the rate of acid deposition, the mean depth of the lake, the input of water directly from precipitation and indirectly from the drainage basin and the effect of the substrate of the drainage basin on any acid deposited there.

The most sensitive lakes are also the shallowest, i.e., the smallest mean depth. If a given amount of acid is deposited on a unit area its effect will decrease with increased depth, or in effect, increased dilution volume. Deep lakes will take much longer to acidify. The amount of rainfall and snowfall determine the amount of rainout and washout acids from the atmosphere. Frequency of occurrence, relative duration and intensity of precipitation are all directly related to the amount of acid precipitation. In the locale of the Shield the amount deposited in snow both by precipitation and by dry deposition is very important. If the amount of acid is relatively high, sudden snowmelt in the spring will release large amounts of acid water which will lower the pH of receiving waters to such an extent that fish kills could result as happened in Norway (40). Snowfall tends to increase from southwest to northeast on the Saskatchewan Shield (an average of 125 to 150 cm annually (62)) but acid deposition tends to decrease with distance from the source of emission so that the actual deposition may remain relatively the same. Heavy local precipitation may lead to higher than expected local acid deposition as was shown to occur in Alberta (Figure 6) and thus effects would be local.

The substrate will have a buffering effect depending on its solubility and the ions made available. There is little buffering by the substrates of the Shield drainage regions while the converse is true off the Shield. Therefore water entering a water body from the atmosphere or from the drainage basin is likely to be similar on the Shield with respect to acidity.

The amount of acid deposited depends on the amount emitted at the source, the height of the stack, plume geometry, the air mass trajectory, the distance travelled from the source and the amounts deposited en route to a specific site. In Saskatchewan 450 km from the source at Fort McMurray, 0.1 kg SO_4-S/ha/yr was deposited in snow which had a pH of 5.0 (at Canwood) (47). This only takes into account acid deposition in snow omitting rain and dry deposition of acid at other times of the year. Esso Resources (15) estimate that sulphur deposition from their projected Cold Lake **in situ** plant (80 t SO_2/day emissions) will be 0.28, 0.26 and 0.13 kg/ha/yr at distances of 200, 300 and 400-500 km respectively from the plant site. (Using this as a comparison the present deposition at 450 km is about 0.5 kg S/ha/yr.) If the number of synthetic crude oil plants is increased as projected (Figure 3), the amount of sulphur fallout will increase by almost eight times from the Fort McMurray plants and more than five times the projected emissions from the Cold Lake Esso plant by the year 2006. The Key Lake area is about 350-400 km from Fort McMurray and Cold Lake. Therefore using the rates of deposition now recorded at 450 km and projected at 400 km, the minimum annual deposition from Fort McMurray would be 0.8 kg SO_4-S/ha and from Cold Lake-Lloydminster 0.65 kg SO_4-S/ha for a total of 1.45 kg SO_4-S/ha. If this is translated into an actual effect on pH, it is equal to about 9 µeq/L of acidity or sufficient to reduce the pH of a lake one metre deep from pH 6.0 to 5.0 in one year if no buffering effect was present. If the lake had a mean depth of 10 m, it would take ten years to achieve the same effect.

However this calculation also ignores any effect of runoff from the drainage basin which could have a greater effect than direct precipitation and dry deposition on the lake itself.

Figure 8

The projected distribution of SO_4-S (Kg/ha/yr) in the year 2006 using the maximum rate of development of Synthetic Crude Oil Production and assuming Flin Flon emissions remain the same. Isolines represent distances of 200, 300, and 400 Km from the source.

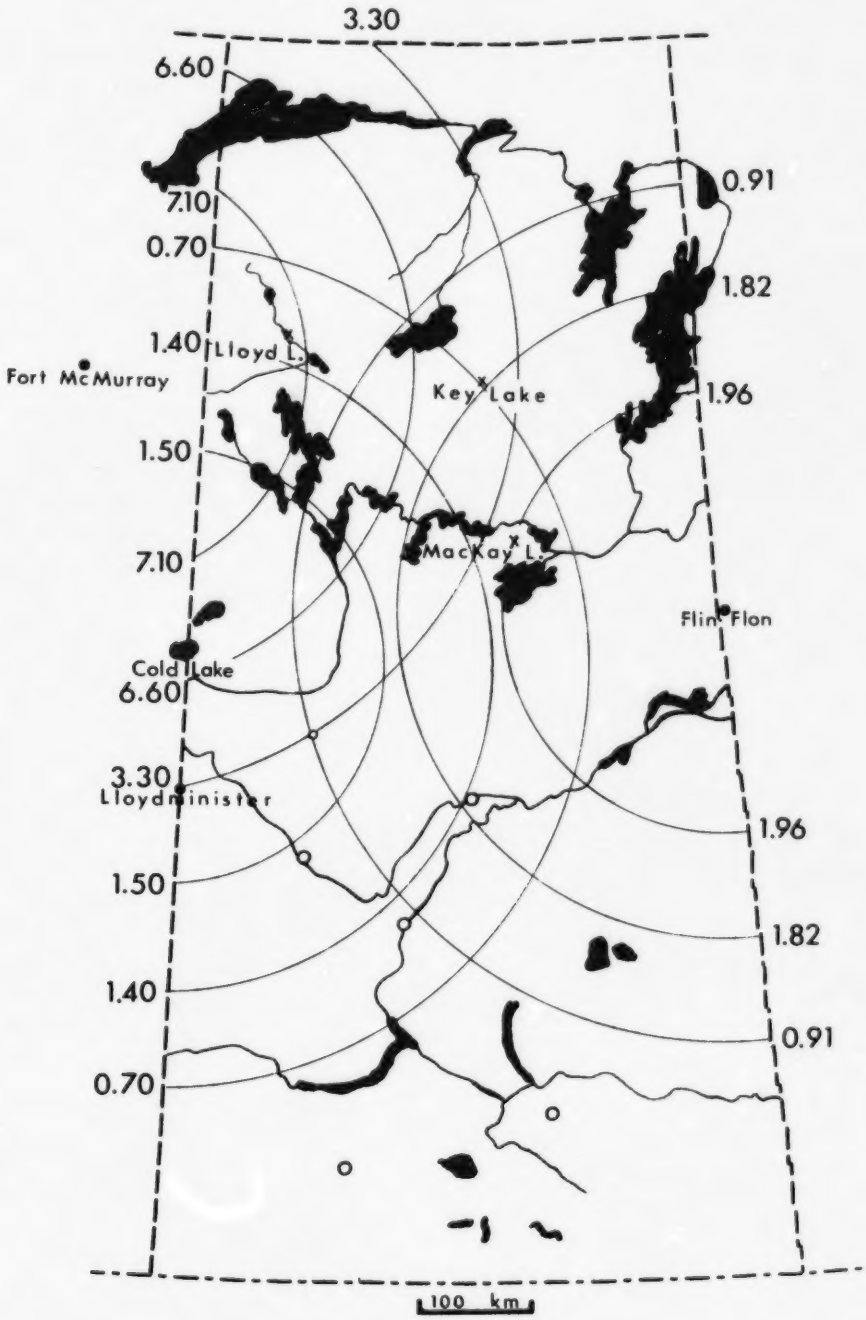


Figure 8 projects the distribution and deposition of SO_4-S in the year 2006 without regard to prevailing wind direction and air mass movements. Rates of deposition are calculated on a proportional basis compared to Esso Resources (15) estimates. Note the intersection of the radiating fallout patterns on the Shield from the two major emission regions. Fallout from the ore smelter at Flin Flon is included as a third major source of SO_2. The latter is largely speculative as there is no evidence at present for this pattern. Prevailing winds and air mass movements may largely preclude such a pattern.

At Key Lake and McKay Lake the combined effect of the three sources would be about 6.4 kg SO_4-S/ha/yr or about 40 μeq/L acidity/yr. At Lloyd Lake in the Clearwater River, the deposition and acidity would be slightly greater, i.e., 8.10 kg S/ha/yr and 50 μeq acidity respectively.

The above calculations also ignore the addition of two heavy oil upgrading plants in Saskatchewan near Lloydminster which are expected to produce SO_2 emissions of about 80 t/day (39). Also ignored are SO_2 and NOx emissions from cities, power generation and other industries. Uranium mine emissions are likely to impinge on the Shield but these are expected to be relatively small and the effects small but cumulative. Table 6 shows the extent of Saskatchewan NOx and SO_2 emissions. They are not expected to change significantly by 1985 (39).

Precipitation Data and their Implications

The Canadian Network for Sampling Precipitation (CANSAP) (6) collects precipitation at three stations in Saskatchewan. These samples are analyzed monthly for their chemical constituents. Table 7 is representative of the data collected. Missing data made it necessary to use two different months in Table 7. Magnesium varied from 0.01 to 0.04 mg/L from November 1977 to December 1978 at Cree Lake (6).

Some significant comparisons between stations are immediately obvious. The pH of precipitation at Cree Lake is almost 2 pH units lower than at the other two stations. The range at Cree Lake from May 1977 to June 1979 was pH 4.6 to pH 6.3 (6). For only three months of this two year period was the pH in excess of 5.6, the expected value for rain at this location.

Ion concentrations are almost always higher at prairie stations than at Cree Lake. This is probably an effect of atmospheric dust on the prairies and the direction of the prevailing winds. Acidic anions (sulphate, nitrate, chloride) are relatively high at all stations but tend to be higher at prairie stations (Table 7). The most significant factor is the low concentration of base cations (calcium, magnesium, sodium, potassium) at Cree Lake. These concentrations are too low to neutralize the acidic anions and this deficiency is then made up by hydrogen ions which lower the pH substantially. At Kindersley and Wynard, on the other hand, base cation concentrations (particularly that of calcium) are much higher providing neutralization of acidic anions and raising the pH of precipitation above uncontaminated rain (5.6) into a range typical of the prairies.

The source of acid anions and other anions is an open question. No sources occur for hundreds of kilometres from the Cree Lake station while local sources on the prairies are small. Long range atmospheric transport seems the likely vehicle and Alberta the probable source of the acid anions in particular. It must also be noted that the CANSAP collectors only collect precipitation events but exclude dry deposition of pollutants (6). Thus the actual fallout of sulphates and nitrates is probably much greater than the CANSAP data appear to indicate.

The average deposition in precipitation of sulphate at Cree Lake was 1.16 mg/L while that of nitrate was 0.47 mg/L during 1978 (from 6). If the annual precipitation at Cree Lake is 30 cm, then the deposition of sulphate in precipitation is 3.48 kg/ha/yr (1.16 kg SO_4-S) while that of nitrate is 1.41 kg/ha/yr. These rates indicate a more serious situation than one would anticipate from calculations based on present emission rates.

Table 6

Emissions of NOx and SO_2 from Saskatchewan sources (tons/year) (39).

	NOx	SO_2
Power Generation		
Boundary Dam, Estevan	27,319	31,400
Estevan	1,641	
Queen Elizabeth, Saskatoon	3,700	6,200
Poplar River (projected)	13,930	23,700
Cities		
Estevan, 1972	598	
Melville	235	
Moose Jaw, 1971	1,730	
North Battleford, 1972	717	
Prince Albert, 1971	1,726	
Regina, 1973	5,084	
Saskatoon, 1971	3,556	
Swift Current, 1972	1,096	
Weyburn	451	
Yorkton	734	
Other sources		
Coop Refinery, Regina	210	4,200
Prince Albert Pulp Mill	3,175	
Gulf Minerals Acid Plant, Collins Bay		360
Totals	65,902	65,860

Table 7

CANSAP data summary for precipitation at Cree Lake (June), Kindersley (May) and Wynyard (June) stations, 1978 (6). Specific conductivity in µS/cm and all ions in mg/L.

Station	pH	Sp. Cond.	$SO_4^{=}$	NO_3^{-}	Cl^{-}	NH_4^{+}	Na^{+}	K^{+}	Mg^{++}	Ca^{++}
Cree Lake	4.8	14.0	2.1	0.33	0.25	0.01	0.3	0.14	—	0.10
Kindersley	6.8	23.6	1.6	0.97	0.70	0.18	0.5	0.06	0.45	2.50
Wynard	6.6	29.0	3.7	4.22	0.50	0.01	0.4	0.17	0.80	2.80

Conclusions

Acid precipitation is presently occurring in Saskatchewan with acid rain as low as pH 4.6. The effect is a progressive deterioration of Precambrian Shield lakes and their fauna and flora and particularly the loss of fish life.

Increasing emissions of SO_2 and probably some NOx from Fort McMurray and Cold Lake-Lloydminster synthetic crude oil developments will only serve to accentuate the problem. The increased use of coal will further worsen the situation. The technology of the removal of acidic gases must be improved drastically to prevent the loss of fish populations from northern lakes. If this is not done, recreation through fishing will be dramatically reduced in the next few decades. Commercial and domestic fisheries, the mainstay of many natives in the north, will likewise be greatly affected.

Acidification of soils and harmful effects on vegetation will probably also occur but the time frame will be much longer. Additions of sulphates and nitrates will probably be beneficial in the short run on the Canadian Shield. Whether selenium deficiencies occur in the Shield is unknown. If they do, sulphur additions will accentuate these deficiencies and will probably lead to harmful effects on wild animals, particularly big game. Sensitive lichens, the food of caribou, may also be adversely affected.

Emissions of SO_2 and NOx and their long range atmospheric transport will probably have fewer harmful effects south of the Precambrian Shield. In fact, sulphur additions in sulphur deficient regions will increase crop yields as will any nitrate additions from the atmosphere. Gradual long term acidification of soils will likely take place but the effect of atmospheric fallout will be minor compared to that achieved by nitrate fertilizer applications. However, acid soils in western central and northwestern Saskatchewan will be adversely affected and reduction of yields and kinds of crops grown will result. Another serious implication of sulphur fallout is with respect to selenium deficient areas. Selenium deficiency in forage and resulting effects on livestock will be accentuated in the northern half of the agricultural zone.

Acidification of lakes in southern Saskatchewan is not anticipated. They are too well buffered. If there is any effect, atmospheric fallout of various chemicals such as nitrates may well increase lake productivity.

Acid precipitation and dry deposition is a serious potential problem in western Canada as well as elsewhere. Its major deleterious effects will be to the Precambrian Shield of Saskatchewan. There, in the long run, we can anticipate lake acidification and drastic reductions in fish populations.

Recommendations

1. That the governments of Canada, Alberta, and Saskatchewan cooperate to the fullest in order to reduce sulphur and nitrogen emissions by various industries in the prairie provinces to a minimum; and
   That air quality standards be rigidly enforced.

2. That industry continue to improve technology to reduce sulphur and nitrogen emissions to the lowest amounts possible.

3. That the number of meteorological network stations be increased to provide better coverage of Saskatchewan with particular attention to the Precambrian Shield region; and
   That stations be established at Fond du Lac, Collins Bay (Wollaston Lake), Island Falls, and La Ronge; and
   That a monitoring program include the amounts of dry deposition of NOx and SOx as well as ion concentrations in various forms of deposition.

4. That the data from the meteorological stations and other sources be used to establish spatial and temporal trends, which would require:
   a) determining the pattern of acidic deposition (wet and dry) of acidic gases and aerosols, and
   b) delineating the oxidation of sulphur dioxide and nitrogen oxides, and their long range transport and trajectories.

5. That a formal program be introduced to determine the lakes in Saskatchewan susceptible to acidic precipitation, the extent of their buffering capacities, and a forecast of deterioration rates under present and future emission and deposition scenarios.

6. That a formal program be introduced to determine the extent of sulphur and selenium deficient soils in Saskatchewan; and
   That the program include a projection of the effects on these soils of sulphur deposition along with the associated effects on crop and animal production.

7. That studies be undertaken on the impact of sulphur deposition on natural flora and fauna in northern Saskatchewan with particular attention to fish, mammals, and their foods.

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